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THE EARTH'S MAGNETIC TAIL

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1.0 Introduction

Detailed measurements of the Earth's magnetic field at geocentric distances up to 31.4 R_e (Earth Radii) have been performed on the nighttime side of the earth by the IMP-1 satellite (Explorer XVIII). The most significant results of these measurements reveal the formation of an extended magnetic tail behind the earth caused by the interaction of the solar wind with the geomagnetic field. A magnetically neutral sheet has been discovered separating regions of oppositely directed magnetic fields in the magnetic tail. The direct relationship of these results to other satellite measurements and related terrestrial phenomena is strongly suggested. An expanded report on these experimental results and presentation of the substantiating data will be presented in a separate publication in the near future.

The magnetic field experiment instrumented for the IMP-1 satellite has already been discussed in a previous publication (Ness et. al., 1964) which should be consulted for a detailed description of the experiment and the initial results. This paper briefly discusses the results obtained from continued operation of the satellite for orbits 20 through 48, corresponding to the time interval Feb. 9 to May 30, 1964. Successful operation of the satellite from November 27, 1963 to May 30, 1964 was terminated due to lack of adequate power from the solar paddle system. Until November 12, 1964 the satellite repetitively cycled in an under voltage mode until the solar aspect angle changed to a more favorable value with respect to power output. From November 12 to December 18, 1964 the satellite has been successfully transmitting both Rubidium vapor and fluxgate magnetometer data. However, these most recent data are not included in this paper.

Certain aspects of the satellite orbit are important in the understanding of the region of space mapped out during the first six months of operation of IMP-1. The orbit is highly elliptical with an apogee of approximately 31.4 R_e and an orbital period of 93.5 hrs. The initial apogee was 25^o west of the sun and due to the heliocentric motion of the Earth precessed approximately 4^o/orbit west of the sun. Thus, on May 2, 1964, apogee was approximately on the earth-sun line on the nighttime side of the earth. However, the satellite moves in an inertial coordinate system so that the relative orientation of the satellite orbit to the ecliptic plane remains approximately the same. Since the apogee lies slightly below the plane of the ecliptic, traversals of the magnetosphere boundary and the collisionless magnetohydrodynamic shock wave enclosing the magnetosphere all occur at low solar ecliptic latitudes. Outbound traversals are below the ecliptic plane by 5-6 R_e and inbound traversals are above by 2-3 R_e.

The Earth's Magnetic Tail

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Abstract: Extensive measurements of the magnetic field of the Earth at distances greater than approximately 7 R_e (Earth Radii) have been performed by the IMP-1 satellite. These magnetic field measurements commenced on November 27, 1963 and terminated on May 30, 1964. During this six month interval the apogee-Earth-Sun angle in solar ecliptic coordinates decreased from 336° to 156°. The apogee of the satellite was 31.7 R_e and the range of the magnetometers between 0.25 to 300 gammas. Previous results of the magnetic field mapping of the magnetosphere boundary on the sunlit hemisphere have been reported (JGR, 69,3531-3569, 1964).

This paper is concerned principally with the topology of the magnetic field within the magnetosphere, and the position of both its boundary and the detached collisionless bow shock wave. The geomagnetic field is observed to trail out far behind the earth in the anti-solar direction, thus forming a <u>magnetic tail</u>. Magnetic field strengths of approximately 10 to 30 gammas are observed out to satellite apogee. The diameter of the magnetosphere at a distance of 30 R_e behind

the Earth is found to be approximately 40 R_e. The direction of the field is parallel to the earth-sun line and in the anti-solar direction below the solar magnetospheric equatorial plane and in the solar direction above this plane. A neutral surface separating antisolar directed fields in the southern hemisphere from solar directed fields in the northern hemisphere has been detected over a large extent in area. This experimental discovery may permit the development of quantitative theories explaining the aurora, gegenschein, day-night asymmetry and formation of the radiation belts. On the basis of a preliminary review of the data it appears that the geomagnetic field trails out far behind the Earth. following the flow field of the solar plasma to a distance far behind the orbit of the moon. No termination of the magnetic tail is detected or suggested by the data. Thus the Earth may be compared to the nucleus of a comet, with the radiation belts and co-rotating magnetosphere being the coma and the magnetic tail being the cometary tail.

2. Observations of the Magnetospheric Boundary and the Collisionless MHD Shock Wave

The interaction of the solar wind with the earth's magnetic field compresses and confines the geomagnetic field to a region of space referred to as the magnetosphere. The existence of an interplanetary magnetic field (Ness and Wilcox, 1964) in the impacting solar plasma leads to the development of a detached collisionless magnetohydrodynamic bow shock wave. The reader is referred to the publications by Ness et. al. (1964) and Bridge et. al. (1964) for a discussion of the observed physical characteristics of these boundaries as observed from orbits 1 through 19 of the IMP-1 satellite. Figure 1 summarizes both these previous measurements and supplements them with data obtained throughout the remainder of the IMP-1 initial six month lifetime. Superimposed on the diagram are the theoretical results computed by Spreiter and Jones (1962) assuming an analogy with the supersonic impact of a continuum fluid but modified to yield a standoff distance equal to that observed. The excellent comparison of the position and shape of the shock on the sunlit hemisphere have been discussed previously. Quantitatively, the positions of the boundary on the night side of the earth do not agree with the theoretical computations. However, it is seen that the magnetospheric boundary, the magnetopause, does not flare out behind the earth at a large angle. Rather it appears to approach asymptotically a boundary with a radius of approximately 20 R_e. The IMP-1 measurements were performed near the sun rise terminator and they are in excellent agreement with the previous results obtained by the Explorer X satellite (Heppner et. al., 1963) when near the sunset terminator. Figure 1 includes the trace of that portion of the Explorer X trajectory over which magnetopause observations were made, as rotated about the earth-sun line.

The mapping of the shock wave boundary as determined only by the magnetic field data apparently terminated following orbit number 21. Unique identification of any observations of the interplanetary medium for orbits 22 through 31 will require a more detailed correlation of the plasma and magnetic field data than is possible at this time. In addition the fact that the solar plasma flow resumes a supersonic and steady flow condition on the flanks of the magnetosphere may further restrict any identification of the collisionless shock wave boundary for these later orbits. A transition from subsonic plasma flow near the stagnation point to supersonic plasma flow downstream occurs and was first observed in the Explorer X plasma results of Bonetti et. al. (1963) as suggested by the interpretation developed by Kellogg (1962).

With the detailed mapping of the magnetospheric boundary around to the nighttime side of the Earth, it is now possible to investigate further the comparison of classical hypersonic flow theory around a blunt object with the observations of the solar plasma flow around the Earth's magnetic field. Indeed, the situation is such that the use of a blunt body such as employed by Spreiter and Jones (1962) and Dryer and Faye-Peterson (1964) may be an unnecessary refinement, at least for shock wave positions on the sunlight side of the Earth when using a gas dynamic analogy.

There is no apriori reason why the center of the Earth should be used to determine a radius of curvature of the magnetospheric boundary near the stagnation point. Thus, a spherical surface has been fitted by least squares to the observed magnetospheric boundary crossings at solar ecliptic longitudes between 270° to 360°. This corresponds to a portion of the sunlit hemisphere of the Earth. In addition the center of the sphere has been assumed to lie on the Earth Sun line at $X = X_c$ ($Y_c = Z_c = 0$). The discrepancy between the observed radial distance to the boundary has been minimized as shown below.

$$\text{Minimize} \quad \left\{ \frac{1}{N} \sum_{i=1}^{N} (R_i - R_c)^2 \right\} \qquad (1)$$

Where R_c = radius of sphere centered at $(X_c, 0, 0)$

$$R_i = \sqrt{(X_i - X_c)^2 + Y_i^2 + Z_i^2}$$

N = total number of boundary crossings (=33)

and i is the $i^{\underline{th}}$ observation of the magnetospheric boundary The result of these computations yielded a sphere with a radius $R_c = 13.9\ R_e$ centered at $X_c = -3.5\ R_e$. The rms deviation is $1.1\ R_e$ which indicates an excellent fit in view of the variability of the solar plasma flow, χ_{ss} and associated variations in the position of the magnetospheric boundary. The observed distance to the shock wave at the stagnation point, with respect to the center of the sphere representing the magnetosphere boundary, is $R_s = 17.4\ R_e$. The standoff ratio($= R_s/R_c$) is thus determined to be 1.25 and is in remarkably good agreement for the theoretical sphere computed by Hida (1953) and others in an hypersonic flow at Mach numbers of approximately 4 to 6. It is suggested, therefore, that in future quantitative studies of the interaction of the solar plasma with the earth's magnetic field use be made of a spherical object approximation to the magnetosphere with a radius of $13.9\ R_e$ centered $3.5\ R_e$ behind the earth. This will permit the use of an analytically more tractable geometry than the blunt body geometry previously employed .

Measurements of the position of both the magnetospheric boundary and the shock wave terminated early in the lifetime of the IMP-1 satellite as the orbit precessed in solar ecliptic coordinates. From orbit number 22 on, the satellite was enclosed within the interaction region surrounding the magnetosphere and from orbit number 31 to 47 the satellite was completely enclosed within the earth's magnetosphere. This "leeward side" or tail region of the Earth's magnetic field shows no indication of any termination at satellite apogee (31.4 R_e).

3. <u>Observations of the Earth's Magnetic Tail</u>

The Earth's magnetic field as distorted by the flow of the solar wind and thereby constrained on the leeward side has been measured during orbits 22 through 48. Over this time interval, from February 17 through May 30, 1964, the Sun-Earth-satellite apogee angle decreased from 253° to 156° as measured by the solar ecliptic longitude. Throughout this time interval a <u>conspicuous</u> and <u>dominant</u> feature of the magnetic field observations was a distortion of the field which may be best described as a draping back of the geomagnetic field into an anti-solar direction. A reasonably representative sample of the type of magnetic field measurements performed and the results obtained is shown in Figures 2 and 3. The magnitude of the field, $\bar{F}$, in gammas, and the solar-ecliptic latitude (θ) and longitude (ϕ) of the field vector are plotted using 5.46 minute averages of the magnetic field (Ness et. al., 1964). These two figures show the magnetic field measurements obtained from April 30 to May 4, 1964 on orbit 41, unique in that it measured the field in a region of space centered about the anti-solar direction and approximately in the midnight meridian plane. The results of the outbound measurements in Figure 2 clearly indicate the tendency of the magnetic field to be in the anti-solar direction since $\theta = 0^{\circ}$ to -5° and $\phi \sim 180^{\circ}$.

The remarkable feature of the Earth's magnetic field trailing out far behind it in space was first observed by the Explorer X satellite measurements in 1961 (Heppner et. al., 1963). More recently, information was published in limited form in a payload coordinate system by Cahill (1964) from the Explorer XIV results in 1963. These measurements indicated that the Earth's magnetic field appeared to be distorted in a manner such that the vector field tended towards an anti-solar orientation on the two sample orbits near the midnight meridian plane. The IMP-1 results reported herein are in agreement with these early measurements and extend dramatically the concept of the magnetic tail of the Earth. As seen in Figure 2 the Earth's magnetic field out to a distance of 31.4 R_e is many times larger than the theoretical field predicted by extrapolation using spherical harmonic coefficients. The two angles θ and ϕ, as previously reported, indicate a very steady anti-solar orientation for the field. Thus, throughout this entire 40 hour time interval the field has been observed to be directed away from the sun. This characteristic feature is evident in <u>all</u> of the IMP-1 data from orbits 31 through 48 during the outbound passes.

After passing through apogee, however, the satellite measurements indicate that at a variable radial distance, from approximately 9 R_e to a maximum of 28 R_e, the direction of the magnetic field changes from an anti-solar to a solar directed orientation. An example of this is shown in Figure 3 as occurring at a geocentric distance of 16 R_e on inbound orbit number 41. Here the magnetic field is seen to decrease to a very small value and to change its direction abruptly, in 20-30 minutes, which corresponds to the motion of the satellite through a fraction of an Earth radius. This abrupt directional change in the earth's magnetic field is identified as the first experimental detection of a neutral sheet in the magnetic tail of the Earth. Such a feature has been recently discussed by Axford, Petschek, and Siscoe (1964) on the basis of an initial suggestion by Dungey (1961) related to connection of geomagnetic field lines with the interplanetary magnetic field. The possibility that the magnetosphere may be open to connection with the interplanetary field has been reviewed by Alfvén (1963).

The significance of the neutral sheet will be discussed in a later paragraph, but its important physical characteristics can be summarized at this time. The neutral sheet is evidenced by both the magnetic field topology within the magnetic tail of the Earth and by its position in the magnetic tail. It has been uniquely observed on 14 of the orbits 31 through 47, and is identifiable on the basis of a very weak or zero magnetic field measured while the field orientation changes from an anti-solar to a solar direction.

The satellite is moving northward with respect to the solar ecliptic pole at approximately 0.5 Km/sec when the abrupt change occurs in the direction of the field from the anti-solar direction in the southern hemisphere to the solar direction in the northern hemisphere. This velocity, multiplied by the time over which the direction changes, yields a "thickness" of approximately 600 Km which is of the order of a proton gyroradius for a 1 Kev particle. This describes a "thin" sheet and is representative of several of the traversals of the neutral sheet

A summary of the magnetic field hourly X_{se} - Y_{se} component averages for the initial 6 month lifetime of IMP-1 is shown projected on the plane of the ecliptic in Figures 4 and 5. Each vector represents the average over one hour with the foot of each vector coincident with the average position of the satellite over the same time interval. These two figures do not permit the full representation of three dimensional magnetic field measurements. However, since θ is generally small and close to zero in the tail, the topology of the field is properly indicated. An attempt to show the three dimensional characteristics of the orbit and the associated spatial sampling of the field is indicated. The dashed lines "contour" the position of the satellite relative to the Z_{se} coordinate of the satellite at the time of measurement. The data in the two figures have been arbitarily separated by the plane $Z_{se} = -2.5\ R_e$ for clarity of presentation. Furthermore, only even hour averages are presented, again for the same reason. Missing data is evidenced for orbits 25, 26 and 37 and is presently being analyzed. The position of the boundary of the magnetosphere is indicated by crosses for each orbital traversal. The two figures essentially present data obtained mainly on the outbound and inbound portions of the 48 orbits respectively. The individual orbits are numbered as shown by the circled numerals.

These figures dramatically illustrate the formation of the Earth's magnetic tail and show the distortion of the field lines quite clearly. The data in Figure 4 present a much clearer view since the satellite was substantially more below the neutral sheet on the outbound than on the inbound passes. The data in Figure 5 show the reversal of the field when the neutral sheet is traversed. In some instances it appears that multiple crossings of a single neutral sheet or separate crossings of multiple neutral sheets are suggested by these data. The former interpretation is favored at present because of the daily "wobble" of the Earth's magnetic dipole axis and its associated effects on the relative satellite position with respect to the neutral sheet. A future publication will discuss in more quantitative detail these magnetic field data. Note that in both Figures 4 and 5 the field appears to closely parallel the magnetospheric boundary indicating little if any normal component of the field.

As has been done in the interpretation of the Explorer X tail data, it is reasonable to consider the magnetic flux observed in the Earth's magnetic tail as coming from the geomagnetic field within the polar cap region. The magnitude of the field observed in the earth's magnetic tail is between 10 to 30 gammas. Assumimg a cylindrical magnetic tail with a diameter of 40 R_e, direct connection to the polar cap lines of force and conservation of total flux from colatitudes of 18^o and less, the predicted tail field strength is about 20 gammas (see figure 6). This value is in excellent agreement with the magnetic field strength observed in the tail and is consistent with the concept that the Earth's magnetic tail is a result of polar cap lines of force being dragged out behind the earth parallel to the Earth-Sun line. Whether or not the lines of force generally parallel a direction aberrated 3^o west of the Sun is indeterminate within the accuracy of the measurements and the limited statistical analyses which have been performed thus far. At a future time it may be possible to indicate more precisely the angle at which the Earth's magnetic tail trails out following the flow field of the solar wind. Walters (1964) has suggested a significant "yaw" because of the oblique interplanetary magnetic field. IMP-1 has not provided evidence to support any large scale effect and indeed direct computation of the predicted effect shows only about an additional 3°-5° to be expected.

4. Position of the Magnetic Neutral Sheet and Related Particle Measurements

If the magnetic axis of the Earth were oriented at all times perpendicular to the plane of the ecliptic it is clear that the neutral sheet would be parallel to and indeed identical to the ecliptic plane. However, the obliquity to the ecliptic of the Earth's spin axis and the non-axial geomagnetic dipole lead to a complex and periodically varying relationship of the orientation of the geomagnetic axis in space relative to the Sun Earth line and the ecliptic plane. The motion in a solar ecliptic coordinate system can be compared to the motion of a gyroscope. As shown in Figure 7 the "precession of the Earth's spin axis occurs in a period of one year with a cone half angle of 23.4^{o} and the nutation of the magnetic axis about the spin axis corresponds to a daily variation with a cone half angle of 11.7^{o}. It is appropriate in the interpretation of the position of the neutral sheet and its physical characteristics to consider this varying attitude. This is a more involved consideration than was used in the initial representation of the position of the magnetospheric boundary as a function of the angle of attack of the solar wind. (Ness et. al., 1964.

Investigators in the field of magnetospheric physics have employed several coordinate systems such as geomagnetic, geographic in the past and more recently solar ecliptic.

This paper will introduce a coordinate system that reflects the control of the magnetosphere and the magnetic tail topology by the solar plasma flow. This new coordinate system is called solar magnetospheric reflecting the importance of the solar plasma flow and the direction of the geomagnetic axis. As shown in Figure 8, the X_{sm}-axis of the solar magnetospheric coordinate system is identical to the X_{se}-axis of the solar ecliptic coordinate system and points from the Earth to the Sun at all times. The Z_{sm}-axis is chosen such that the X_{sm} - Z_{sm} plane always includes the geomagnetic dipole axis. Thus, the Y_{sm} axis of the right-handed coordinate system is always orthogonal both to the Earth-Sun line and to the geomagnetic dipole axis. Within this coordinate system it is possible to define equivalent latitudes and longitudes of the position of the neutral sheet as traversed by the IMP-1 satellite.

The relative position of the neutral sheet in the Earth's magnetic tail is an important parameter is ascertaining its relationship to terrestrial phenomona and other satellite measurements. This orientation has been investigated with solar ecliptic, geomagnetic and solar magnetospheric coordinates using χ_{ss}, the geomagnetic latitude of the subsolar point as an independent variable. The results of this progressive study are shown in Figures 9-11. The solar magnetospheric coordinate system gives the best fit of the neutral sheet to an equatorial plane in the three coordinate systems studied. In the solar ecliptic coordinate system shown in Figure 9, the subsatellite latitude of the neutral sheet traversal was observed between 3^{o} and 22^{o}. In the geomagnetic coordinate system shown in Figure 10, the geomagnetic latitude of the subsatellite point appears to be much better ordered than was observed in the solar ecliptic coordinate system. However, the subsatellite latitudes still extend over the geomagnetic range $+5^{o}$ to -25^{o}. The inverse dependency of the neutral sheet geomagnetic latitude upon χ_{ss} suggested the solar magnetospheric coordinate system.

Figure 11 shows the result in the solar magnetospheric coordinate system and a clear result is obtained indicating that the neutral sheet is almost identical to the solar magnetospheric equatorial plane (within 5^{o} or 10^{o}). The departure of the neutral sheet from being within a few degrees of this equator for higher geomagnetic latitudes of the sub-solar point may be related to a spatial curvature or warping of the neutral sheet surface caused by an increased angle of attack of the solar wind as measured by χ_{ss}. This departure could also be an inherent aspect of the of the neutral sheet in that it is not a flat planar feature in the Earth's magnetic tail. No attempt has been made to remove any transient variations of the neutral sheet position from these data although magnetic activity has been significant during these measurements. The suggestion by Frank (1964) and Singer et.al. (1964) that an anti-solar tail of energetic electrons was oriented preferentially in the ecliptic plane is probably only partially correct. The orientation is probably more nearly in the solar magnetospheric equatorial plane and reanalysis of these data should indicate this to be the case. Recently Montgomery et. al. (1965) have revised their original analysis and suggest that the results now indicate an orientation closer to the geomagnetic equatorial plane. However, they have yet to employ solar magnetospheric coordinates. Only with satellite measurements during the equinoxes and the solstices can the analysis reveal the correct neutral sheet orientation.

The most important feature of these IMP-1 measurements, however, extending over distances from 9 to 28 R_e during a three month interval is that the neutral sheet is a permanent feature of the Earth's magnetic tail and that it separates regions of appreciable field strength which are oppositely directed. For stability of field lines outside this neutral sheet it is necessary that an enhanced plasma flux be present. Indeed Axford et.al. (1964) suggest that previous satellite measurements on the anti-solar side of the earth by Frank (1964) and Singer et. al. (1964) may be an indirect reflection of the magnetic tail field topology Although Dessler (1964) and Dessler and Juday (1964) implied that a neutral sheet would develop in the tail, they did not state this explicitly as did the previous authors. Pressure balance requires that the region of space separating fields of opposite direction contain an enhanced particle population. An attempt to compare directly those measurements of particles on the night side of the earth which relate to this problem follows.

Essentially the neutral sheet appears to be a possible repository and/or source for energetic particles which may permit an explanation of such phenomenon as the aurora and the development of the trapped radiation belts as well as their observed day nite asymmetry. The paper on geomagnetic storm theory by Piddington (1960) presented a magnetic field topology in the tail which is in good agreement with the IMP-1 observations. The possibility of such a permanent magnetic field topology, however, appears to have been overlooked by him somewhat as did Chapman and Ferraro in their development of a transient geomagnetic cavity more than 30 years ago. Satellites and space probes have permitted the time scale since Piddington's early suggestion to be considerably shortened to approximately 5 years.

Figure 12 illustrates the electron flux values at a specific energy which would correspond to balance of transverse particle pressure and the pressure of the oppositely directed magnetic fields in the tail of the earth. This model of the magnetic tail essentially considers the neutral sheet to be a flat slab of isotropic thermalized plasma separating the northern and southern hemisphere portions of the tail in a static configuration. If it is assumed that there is no plasma within the magnetic field and vice versa the transverse pressure balance is described by $P_{\perp} = B^2/8\pi$. This simple model will yield minimum values of the expected particle fluxes in the neutral sheet. Superimposed on Figure 12 are the results of previous satellite observations. The Lunik II data, obtained at low geomagnetic latitude in the tail of the Earth, probably represent the neutral sheet rather than a third radiation belt (Gringauz, 1964; Van Allen, 1964).

It is seen that there is a reasonable level of consistency among the various pertinent experimental results, to within their respective accuracies. The data of Explorer XII showed a definite effect due to low energy electrons in the magnetospheric tail. The mean directional intensity inferred from the observations on a particular day of high intensity was approximately 10^9/cm^2/sec/sterad if the effect was attributed to

10 Kev electrons (Freeman, 1964). On the basis of a general review of Explorer XII data Frank and Van Allen (1964) concluded that intensities of perhaps one lower order of magnitude were more representative of the usual level in this region.
Freeman (private communication) has pointed out that if it is assumed that the magnetic field was stronger at the appropriate Explorer XII positions (and indicated by IMP-1 to be true) then the agreement is quite good.

It is also clear that the suggestion by Van Allen (1964) that the particles observed by Gringauz et. al. (1960) or Lunik II are related to those observed on the Explorer XII satellite is in excellent agreement in the general trend of particle measurements. In addition the Explorer XIV measurements reported by Frank (1964), and Anderson et.al. (1964) at much higher energies indicate that this picture of a neutral sheet of highly energetic electrons may well be the direct result of the dragged out magnetic field lines from the polar cap regions of the earth's magnetic field. The exact mechanism for this extension of field lines is not clear although Axford and Hines (1961) suggest that it is due to "viscous drag" of the solar wind on the magnetospheric boundary. The possibility that reconnection of field lines between geomagnetic and interplanetary regimes is the primary mechanism must also be considered.

Detailed correlations of the results of the various experiments on the IMP-1 satellite are being performed to deduce further properties of the Earth's magnetic tail and its neutral sheet. An important aspect of the development of such a neutral sheet in the Earth's magnetic tail is the question of its inherent stability. A type of resistive instability studied in the controlled thermonuclear fusion program by Furth, Killen and Rosenbluth (1963) shows a very similar field and plasma geometry which may lead to acceleration of particles and thus to a propagation along the field lines into the auroral zones. Petschek (1963) has discussed magnetic field annihilation across a neutral sheet as a mechanism for acceleration of particles, converting magnetic energy to plasma energy. It is suggested that a neutral sheet populated with a relatively high density and energetic plasma possesses inherent instabilities which may lead to acceleration of particles and thus permit an explanation of the auroral phenomenon. This significantly differs from the mechanism proposed by Dessler and Juday (1964) who argue for an energizing of particles at the magnetosphere boundary.

Piddington (1960) also suggested that the earth's magnetic tail is a related mechanism for the formation of the earth's gegenschien as due to the electrons in the tail. Gindilis and Kayagina (1964) have recently reviewed and revised earlier work on the observations of the gegenschein and removed a substantial portion of the support for such an origin by showing that the observed spectrum is dust scattered sunlight.

Van de Hulst (1956) suggested that the gegenschein origin might well arise in a gas tail of the earth, although little observational support existed at the time. Shklovsky (1959) considers the source of Lyman α to possibly originate in a gas tail of the earth rather than from a distribution of hydrogen in interplanetary space. Related aspects of a gas tail of the Earth have been summarized by Brandt (1961) and estimates of the geometrical dimensions have been given which in general are in agreement with the IMP-1 measurements reported for the Earth's magnetic tail.

Future studies on the intimate relationship of these various particle and visual phenomenon to the solar magnetospheric equator and observations of the neutral sheet and its properties by future satellites will be very important in confirming these general introductory remarks on the significance of the Earth's magnetic tail and its similarity with cometary tails.

5. Summary and Conclusions

The detailed measurements of the Earth's magnetic field on the nighttime side of the Earth by the IMP-1 satellite have revealed a strong and steady magnetic field of 10 to 30 gammas. The field is directed either away from the sun or towards the sun depending upon whether the satellite is below or above a magnetically neutral sheet. The discovery of the neutral sheet is an important aspect in the determination of the earth's environment in space and the interaction of the super Alfvenic solar plasma with the earth's magnetic field. Many questions remain with regard to the full significance of the neutral sheet and the magnetic tail but collectively they appear to offer obvious possibilities for explaining a number of terrestrial phenomena which have been studied in the past and are known to be solar related. The inherent instability of such a neutral sheet has been studied in the controlled fusion program where such a magnetic field topology and plasma is described as a sheet pinch of type B1 (Furth, 1963).

The characteristics of an extended Earth's magnetic tail suggest that the interaction of the solar plasma with the geomagnetic field possibly may be compared to a comet in which the Earth corresponds to the nucleus. The trapped particles spiraling about lines of force connected to the Earth's surface and drifting in longitude around the Earth periodically, correspond to the coma and Earth's magnetic tail corresponds to the cometary tail. Alfvén (1957) and Marochnik (1961) have already suggested that the impact of the magnetized solar plasma with a comet may provide shock wave mechanisms and magnetic field topologies which can explain the type I cometary tails observed. It is further suggested in this paper that a study of the role of the neutral surface or sheet in the acceleration of particles and in the confinement of plasmas may find a parallel in the study of cometary tails. The superposition and capture of the interplanetary magnetic field as proposed by Alfvén (1957) may lead to a cometary tail with multiple neutral sheets since the direction of the field changes periodically (Ness and Wilcox, 1964).

A summary presentation of the magnetic field topology within the Earth's magnetic tail projected in the plane of the ecliptic is shown in Figure 13. The boundary of the magnetosphere is represented by a heavy solid line although as indicated by previous measurements on IMP-1 (Ness et. al., 1964) appreciable magnetic field energy appears to be capable of being transmitted across the boundary. As noted by Serbu (1964) there is experimental evidence that the boundary is permeable to low energy particles on the basis of flux measuerments $>$ 100ev. performed on IMP-1. Near the stagnation point, the magnetospheric boundary is identical to the boundary of intense higher energy trapped particle flux

($>$ 40 Kev). Away from the subsolar point these two boundaries gradually separate until at the 0600-1800 meridian plane the difference is 5 R_e (Anderson et. al., 1964). Figure 13 also shows the shape of the collisionless shock boundary as observed by IMP-1 and the traces of the 47 orbits of the satellite from which the data have been obtained to yield the indicated results. Orbit number 48 was not completed before the satellite transmission terminated and hence has not been included in the graphical presentation. The important features are the turbulent transition region between the magnetosphere boundary and the collisionless shock. A change to a more organized field configuration compatible with compression of the interplanetary magnetic field lines within the transition region as the solar plasma resumes supersonic flow far from the stagnation point is indicated.

A schematic summary of the noon midnight meridian plane magnetic field topology and neutral sheet location is shown in Figure 14. The magnetosphere is shown compressed on the sunlit side of the Earth and terminated at approximately 10 R_e by the impact of the solar wind. The thickness of the region of turbulence, bounded by the collisionless shock wave, is observed to be approximately 3.4 R_e and the shape of the two surfaces is such that representing the magnetosphere as a sphere of radius 13.9 R_e yields a detachment ratio which is comparable to that for a sphere in hypersonic flow at the corresponding Mach number. On the nighttime side of the Earth the geomagnetic field is shown to be dragged out from the polar cap regions and to be extended behind the Earth to limits as yet unmeasured. It is clear that termination of the Earth's magnetic field does not occur within the lunar orbital distance. Dessler (1964), on the basis of balance of magnetic pressure interior to the magnetospheric tail with that of the interplanetary pressure predicts tails lengths of 20 to 50 A.U. Although lengths of this extreme magnitude are highly speculative, it is not incorrect to consider the Earth's magnetic field as being long relative to the Earth-Moon distance ($\approx 2.5 \times 10^{-3}$ A.U.). How far it extends into interplanetary space is certainly limited to the distance at which the solar wind terminates and to whether or not the Earth's magnetic tail is an exact parallel of a cometary tail.

The magnetic field topology as shown in Figure 14 indicates a prominent day night asymmetry both in the distribution of auroral zone phenomenon and in the trapped particle trajectories. Such day-night asymmetries have already been observed by O'Brien (1963), McDiarmid and Burrows (1963), Frank et. al., (1964), Freeman (1964) and others. The exact relationship of the magnetosphere and

and its boundary near the northern and southern polar regions is unknown and presently unprobed. Although the illustration in Figure 14 indicates a depression of the boundary associated with the two neutral points in the polar regions its location is not known. Following the general discussion outlined by Piddington (1960) it may be possible to develop a geomagnetic storm theory invoking the magnetic tail of the earth, the neutral sheet and their changes as an explanation of the main phase of geomagnetic storms.

It is interesting to note that Biermann (1951) studying type I cometary tail observations predicted a solar corpuscular flux which today is now a well accepted feature of the interplanetary medium : the solar wind (Parker, 1963). It is reasonable to expect that by detailed measurements of the Earth's magnetic tail with satellites the study of cometary tails can be further advanced. The argument at present is that the two tail structures are similar physical phenomena resulting from the interaction of the solar wind with two different types of celestial objects. The major difference between the earth and a comet is probably the inherent internal magnetic field of the Earth and the absence of a similar magnetic field of a comet. The coma results from evaporation of materials from the surface of the comet whereas the radiation belts result from the entrapment of charged particles in the dipolar magnetic field topology. Certainly these new concepts bring fresh insight into the study of physical processes important both in comets and the Earth's space environment.

In the case of the Earth the inherent dipolar magnetic field leads to the development of the magnetosphere while in the case of comets of type I, evaporation of the nucleus forms the ionized coma which captures the interplanetary magnetic field. At the present time neither mechanism finds an obvious parallel in the case of the Moon. Thus, although a lee wake of the Moon will develop in the flow of solar plasma, a lunar magnetic tail does not appear to be permanent feature of the Moon. The experimental data on the existence of a magnetohydrodynamic wake of the Moon has been discussed recently from IMP-1 observations by Ness (1965). It is now clear that the Moon always crosses the Earth's magnetic tail and hence lunar related phenomena in the magnetosphere and on the terrestrial surface can be expected on this basis rather than on any possible tail of the Moon interaction with the Earth. Other planetary objects may create wakes in the solar plasma flow but will probably not possess magnetic tails. This is certainly true for Mercury and Venus. Mars may have and Jupiter in all probability does possess a significant magnetic tail because of its magnetic field.

Acknowledgements

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Figure 5. Projection of X_{se}-Y_{se} component of magnetic field as measured by IMP-1 onto ecliptic plane when satellite is above $Z_{se} = -2.5\ R_e$ and within the magnetosphere and tail region. Crosses indicate traversal of magnetospheric boundary; circles indicate orbit numbers. (See text)

Figure 6. Theoretical prediction of field strength in earth's magnetic tail assuming connection of polar cap flux into tail. The tail is taken to be a cylinder of radius R_T and the colatitude of the polar cap region is indicated by θ .(See text)

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Figure 10. Relative position of the neutral sheet as observed on 14 traversals by the IMP-1 satellite during orbits 31 through 47. The geomagnetic latitude of crossing is plotted as a function of the geomagnetic latitude of the subsolar point.

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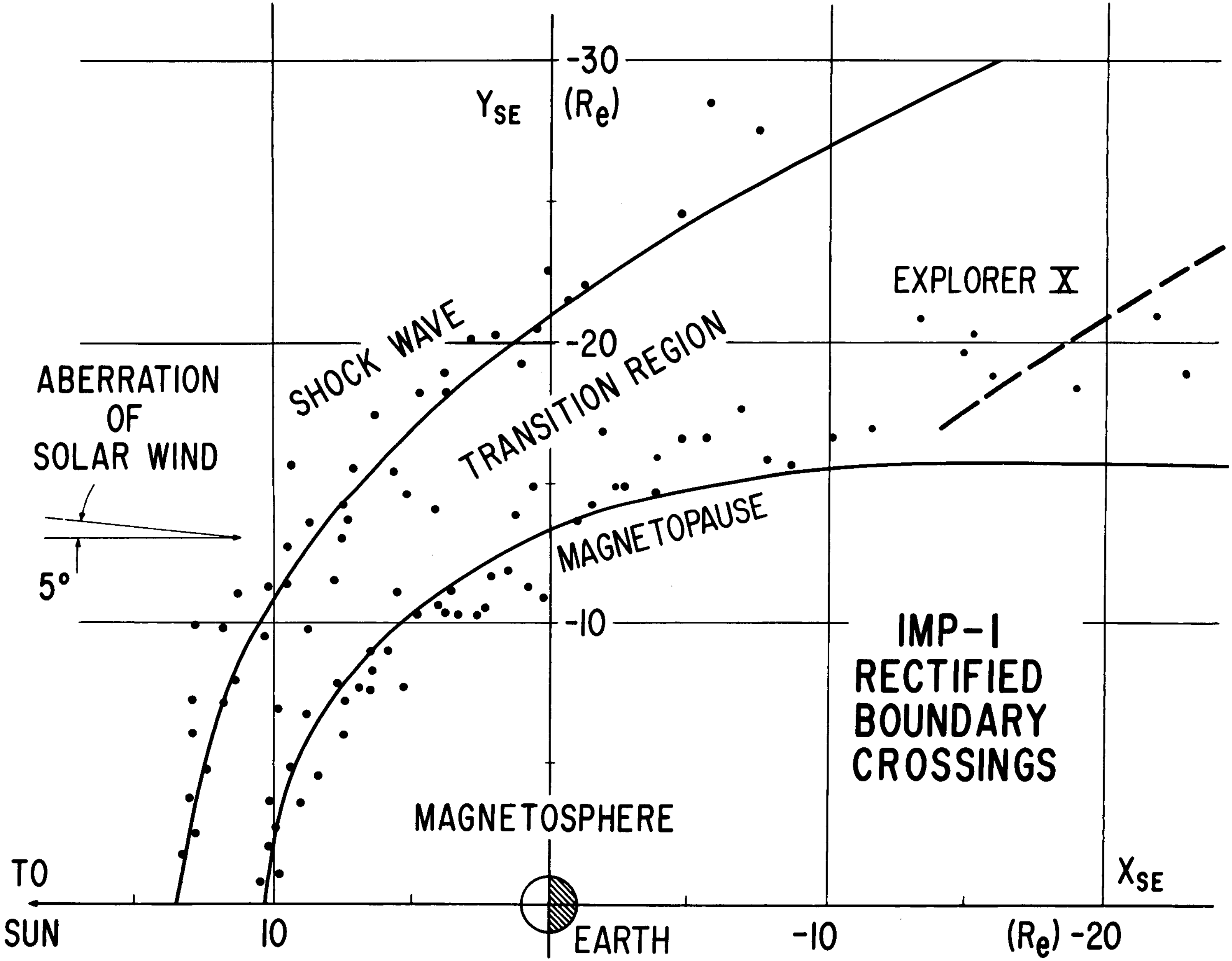
Figure 12. Composite of electron flux measurements observed on the nighttime side of the earth suggested as obtained while within the neutral sheet. Superimposed are the magnetic field strengths consistent with a simplified model of the neutral sheet as a

stable "sheet pinch" plasma separating oppositely directed magnetic fields of specified strength.

Figure 13. Illustration of the interpretation of the IMP-1 magnetic field data, the field topology within the magnetosphere and the interaction of the solar wind with the geomagnetic field. The magnetic field topology is shown projected on the ecliptic plane and represents field lines from the southern polar cap region extending out to form the magnetic tail of the Earth. The distances to the two boundaries at the stagnation point are 10.25 R_e and 13.4 R_e respectively.

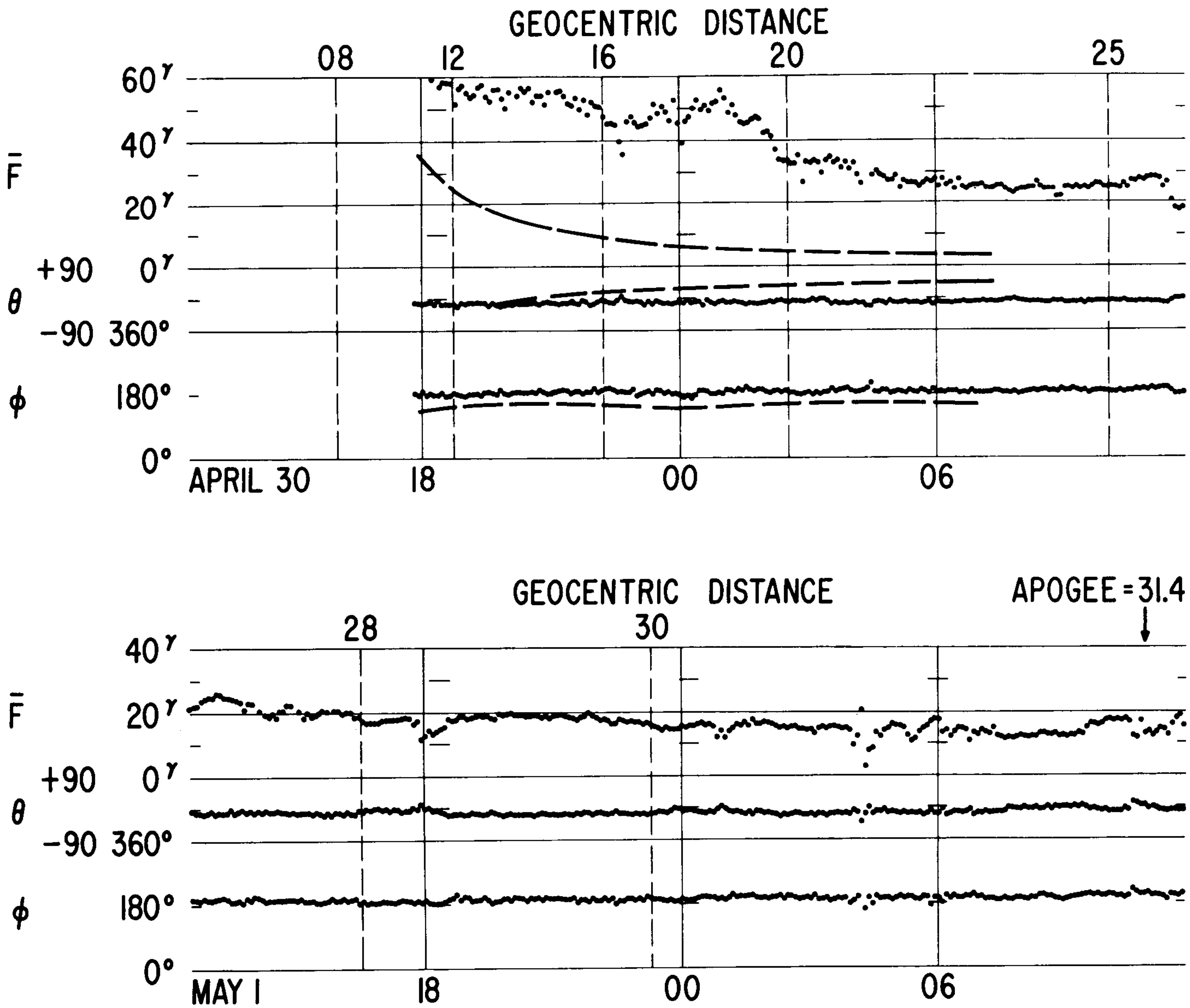
Figure 14. Illustration of the interpretation of the IMP-1 magnetic field data field topology within the magnetosphere in the noon-midnite meridian plane. The relative position of the neutral surface or sheet in the Earth's magnetic tail and the co-rotating magnetic field lines supporting trapped particle motion are indicated. These include the classical Van Allen radiation belts. The collisionless shock and magnetosphere boundaries are extrapolated to the polar regions indicating a depression but the relative position of a polar neutral point and the size of the boundary are not experimentally

determined. Cylindrical symmetry about the Earth Sun line has been assumed for the boundary of the Earth magnetic tail in this presentation.



-30
Y_{SE}
(R_e)
-20
-10
ABERRATION
OF
SOLAR WIND
5°
SHOCK WAVE
TRANSITION REGION
MAGNETOPAUSE
EXPLORER X
IMP-I
RECTIFIED
BOUNDARY
CROSSINGS
MAGNETOSPHERE
TO
SUN
10
EARTH
-10
(R_e) -20
X_{SE}

Figure 1



ORBIT NO. 41 IMP-1 1964

Figure 2

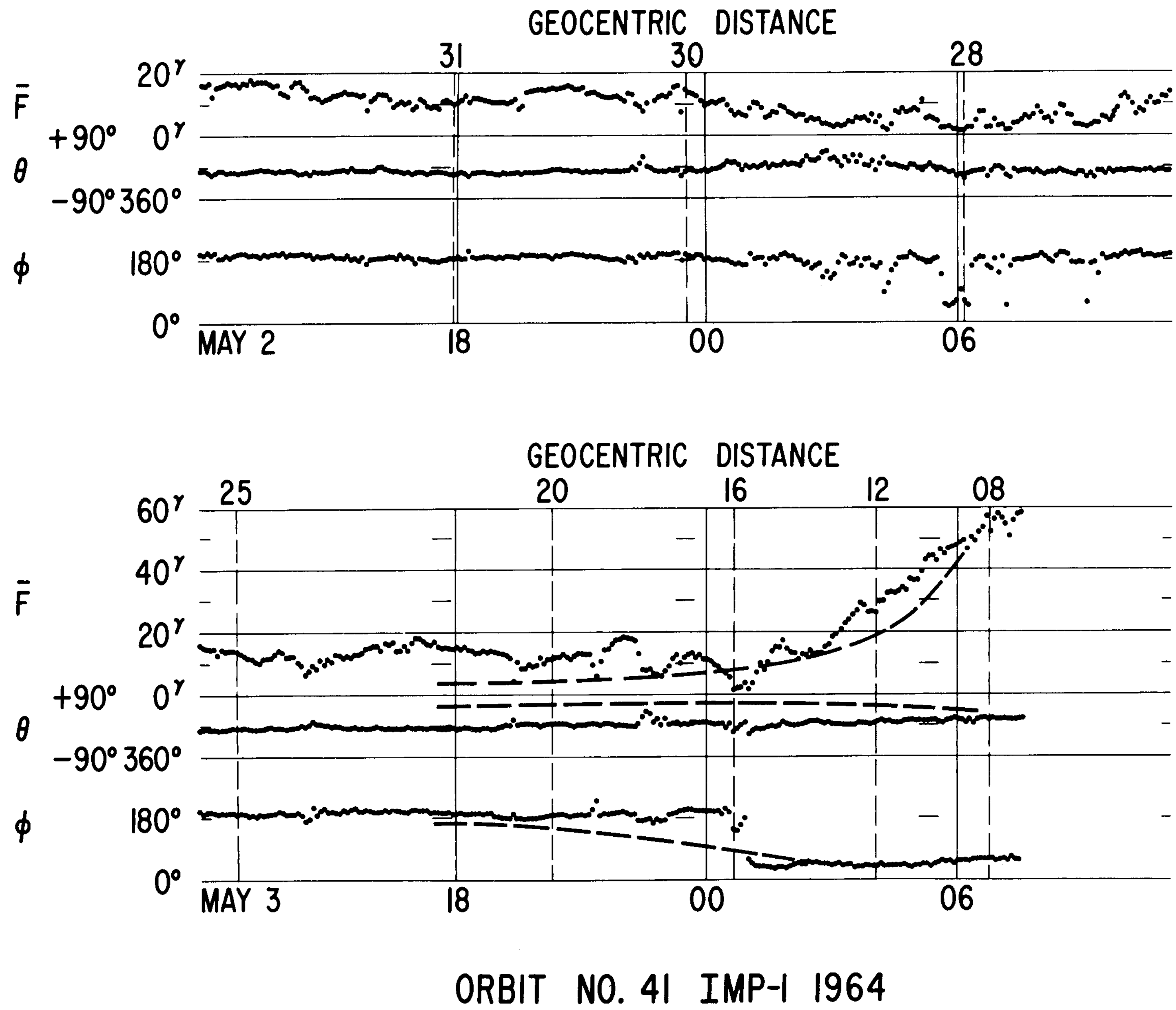
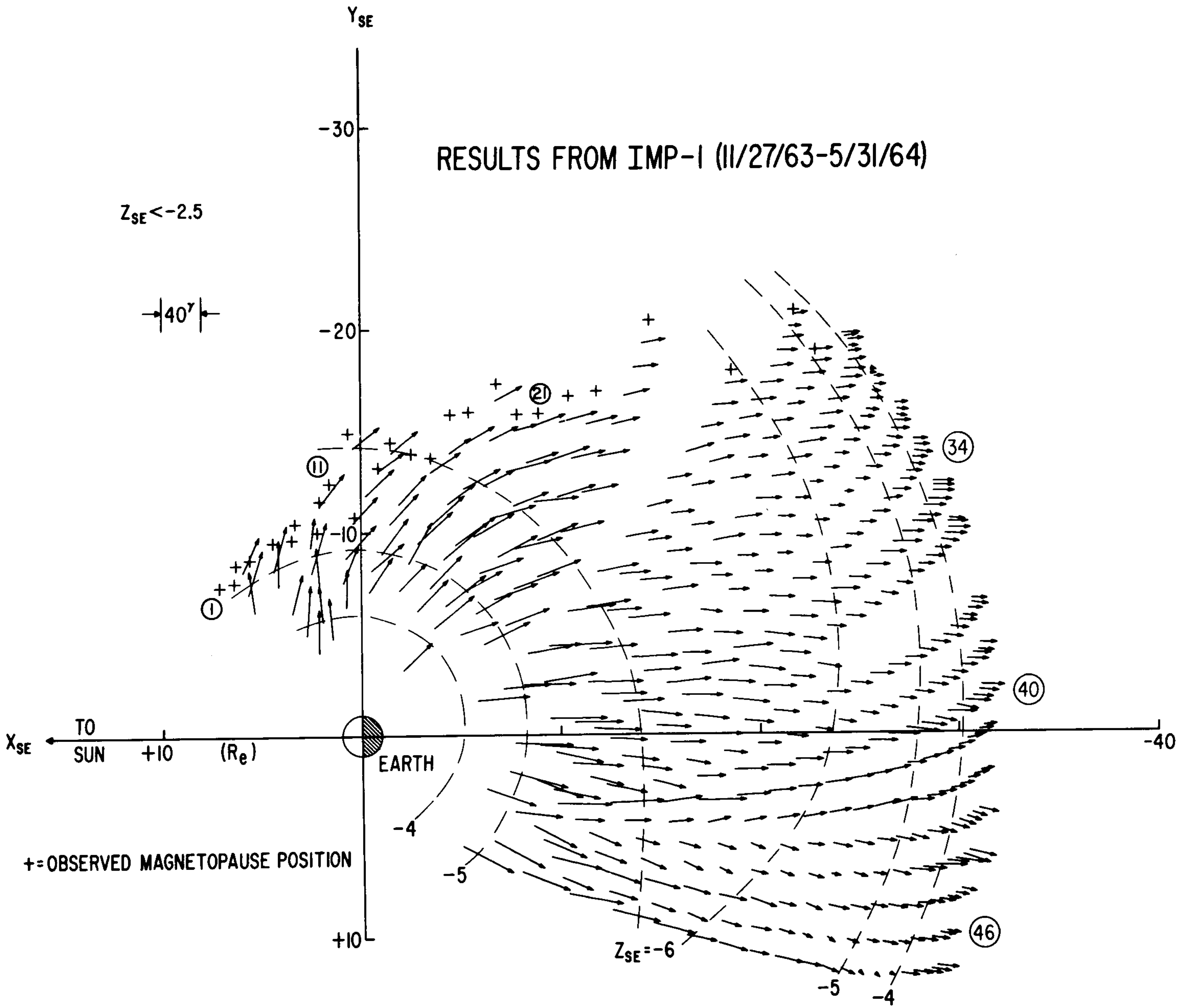
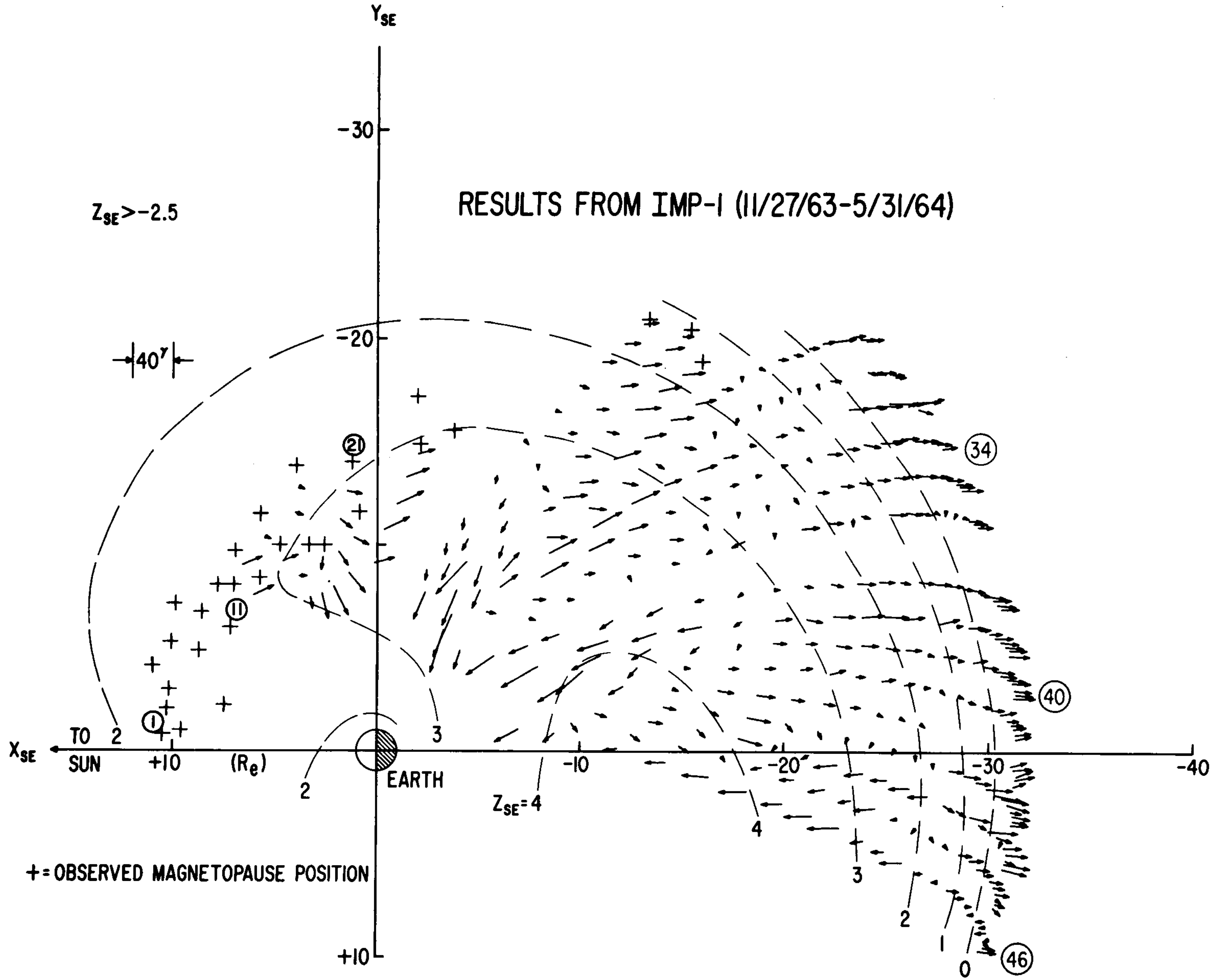

GEOCENTRIC DISTANCE
31
30
28
$\bar{F}$
20γ
0γ
θ
+90°
−90°
360°
φ
180°
0°
MAY 2
18
00
06
GEOCENTRIC DISTANCE
25
20
16
12
08
$\bar{F}$
60γ
40γ
20γ
0γ
θ
+90°
−90°
360°
φ
180°
0°
MAY 3
18
00
06
ORBIT NO. 41 IMP-I 1964

Figure 3



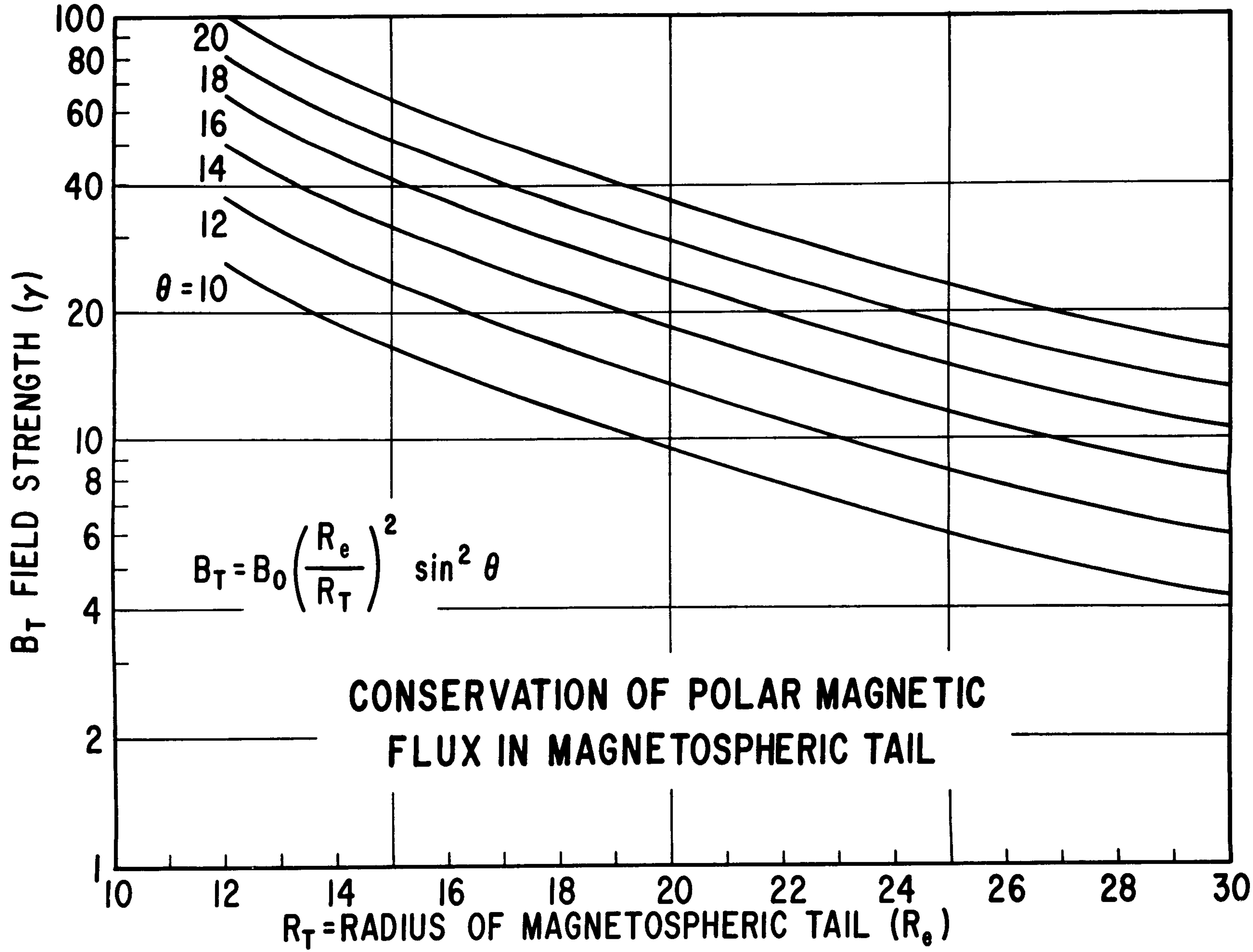
$X_{SE}-Y_{SE}$ COMPONENT OF MAGNETOSPHERE FIELD

Figure 4



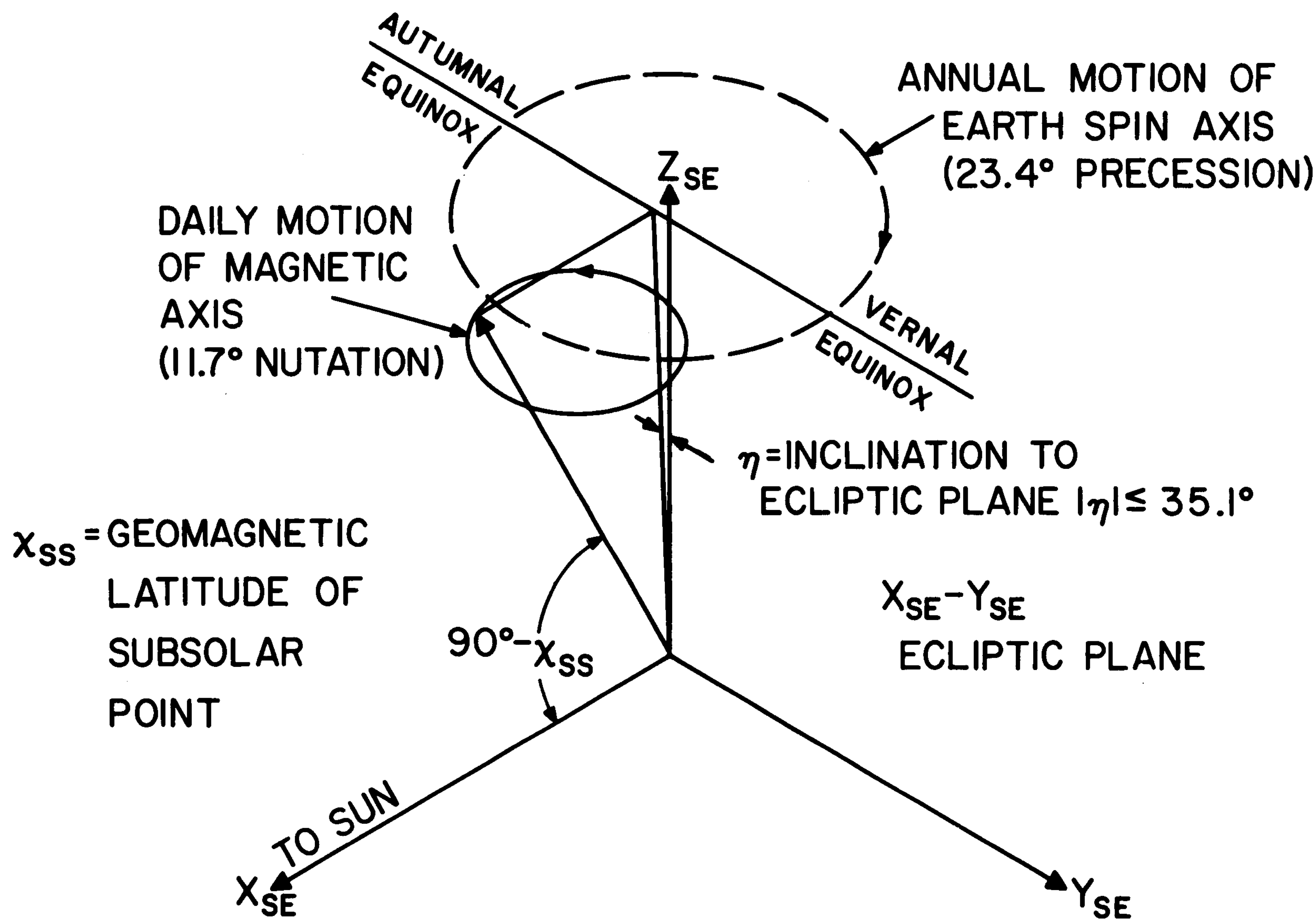
X_{SE}-Y_{SE} COMPONENT OF MAGNETOSPHERE FIELD

Figure 5



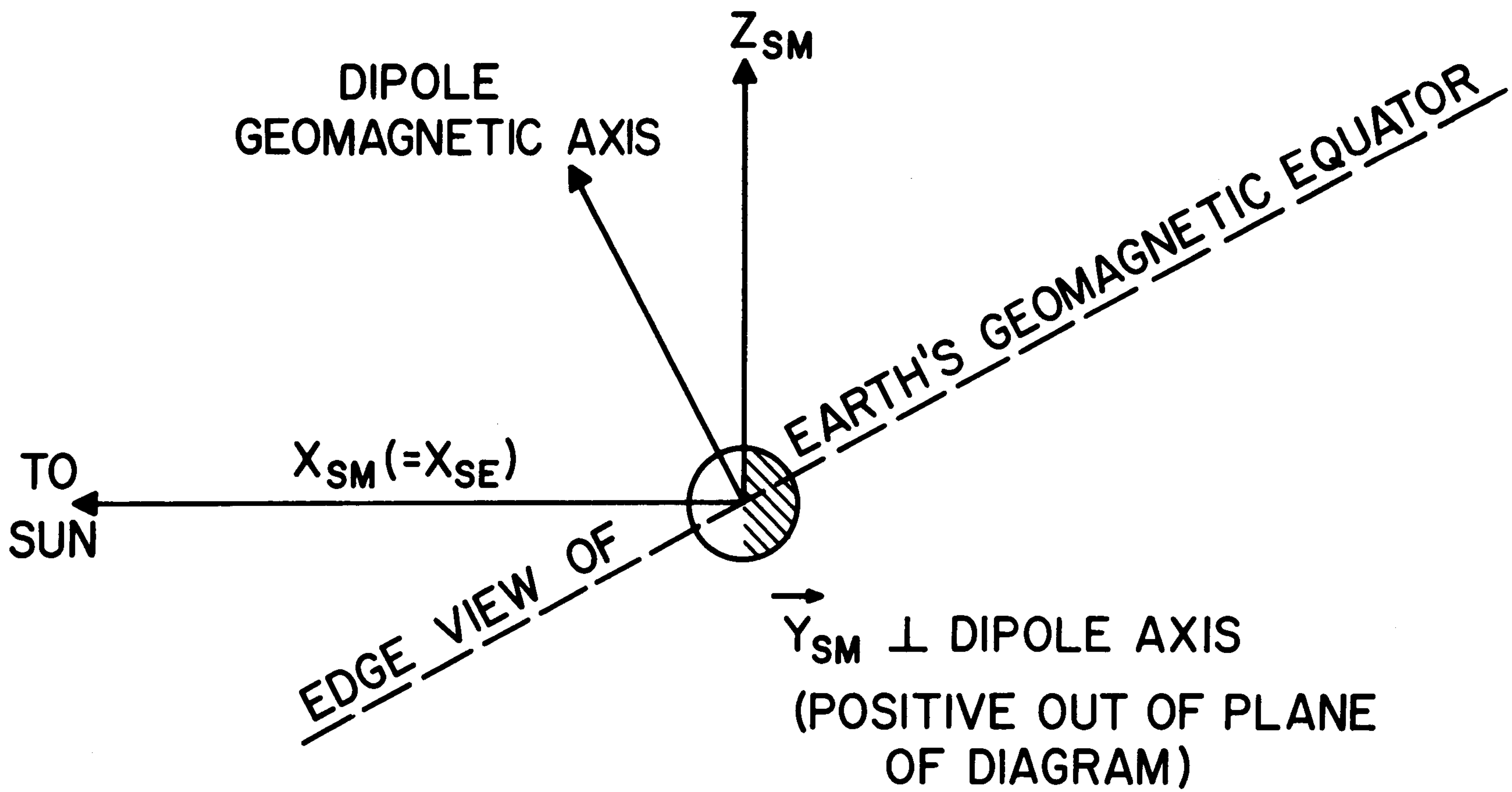
CONSERVATION OF POLAR MAGNETIC
FLUX IN MAGNETOSPHERIC TAIL
$B_T = B_0 \left(\frac{R_e}{R_T}\right)^2 \sin^2 \theta$
$\theta = 10$
12
14
16
18
20
B_T FIELD STRENGTH (γ)
1
2
4
6
8
10
20
40
60
80
100
10
12
14
16
18
20
22
24
26
28
30
R_T = RADIUS OF MAGNETOSPHERIC TAIL (R_e)

Figure 6



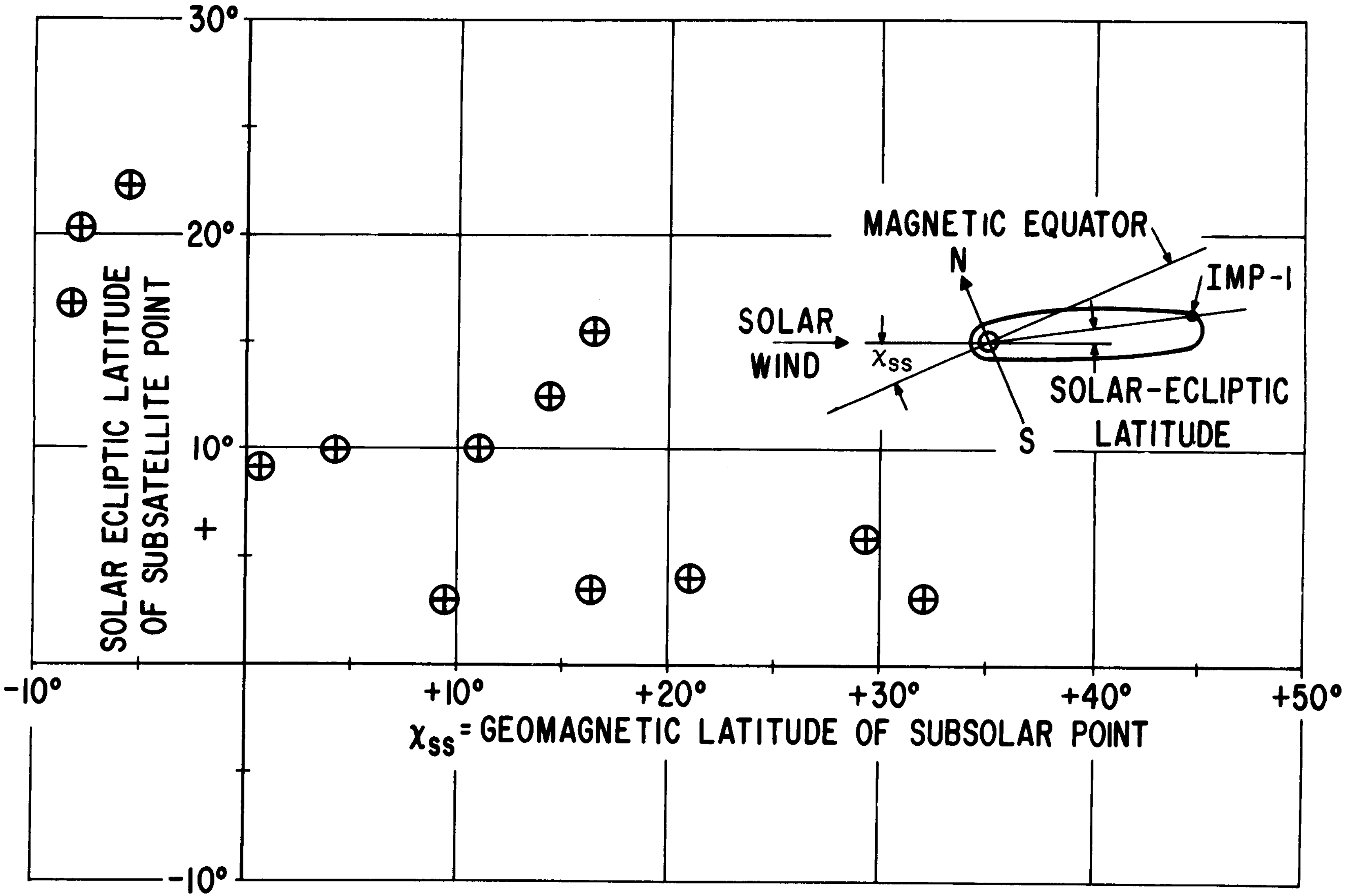
MOTION OF MAGNETIC AND SPIN AXIS
IN SOLAR ECLIPTIC COORDINATES

Figure 7



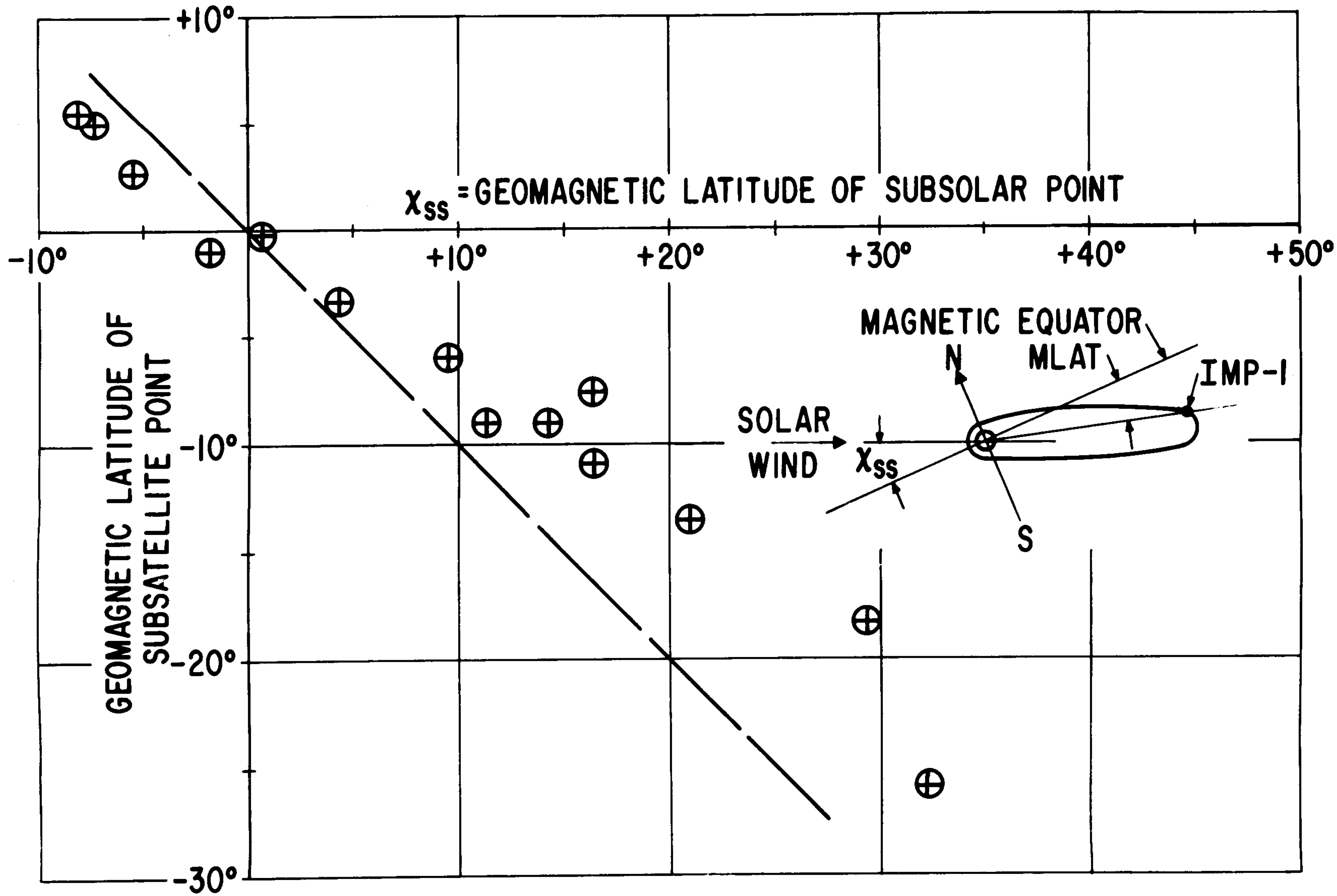
SOLAR MAGNETOSPHERIC COORDINATE SYSTEM

Figure 8



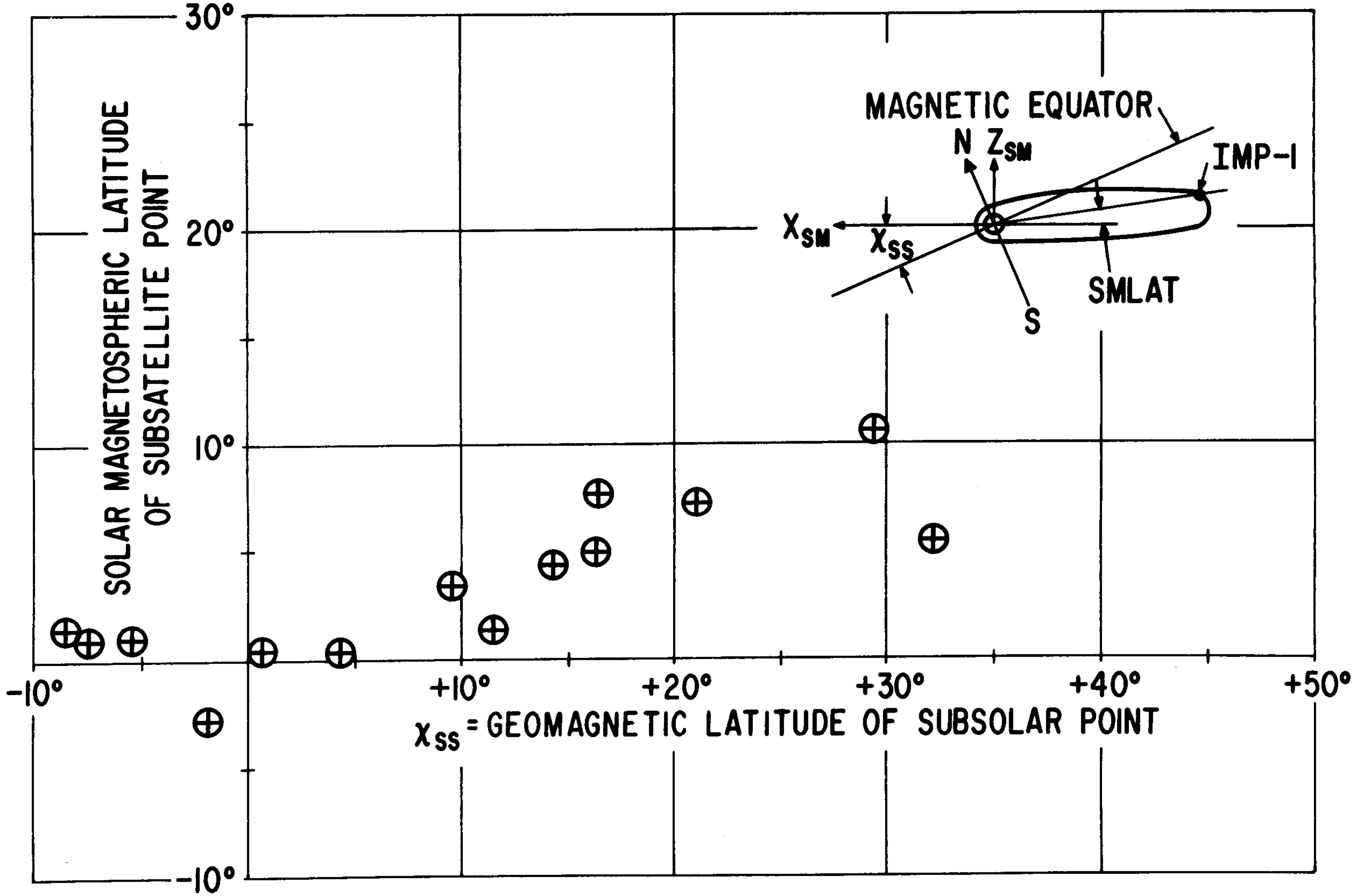
RELATIVE POSITION OF NEUTRAL SHEET

Figure 9



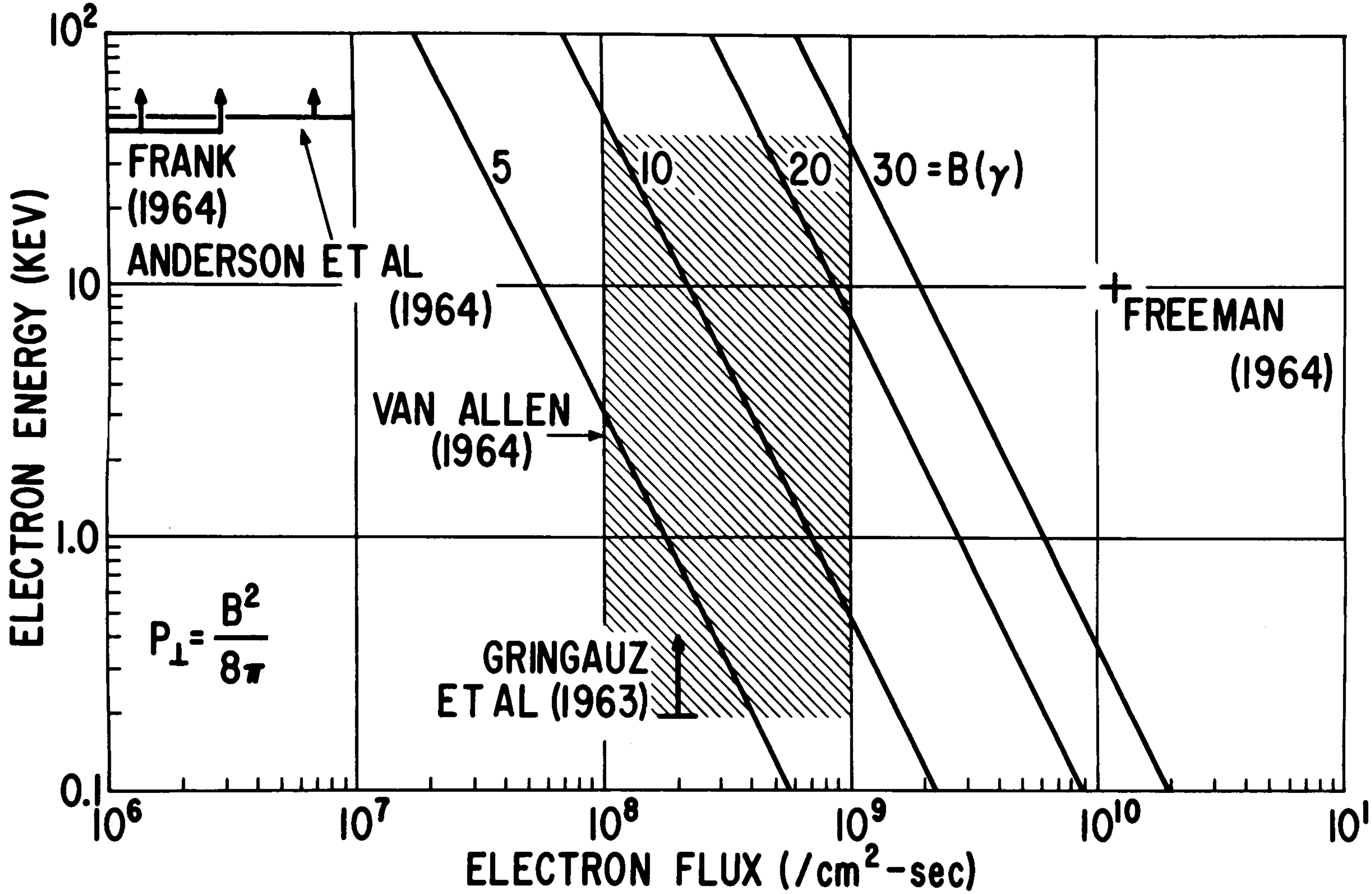
RELATIVE POSITION OF NEUTRAL SHEET

Figure 10



RELATIVE POSITION OF NEUTRAL SHEET

Figure 11



ELECTRON ENERGY (KEV)
ELECTRON FLUX (/cm²-sec)
FRANK (1964)
ANDERSON ET AL (1964)
VAN ALLEN (1964)
GRINGAUZ ET AL (1963)
FREEMAN (1964)
5
10
20
30 = B(γ)
P⊥ = B²/8π

Figure 12

RESULTS OF IMP-1 MAGNETIC FIELD EXPERIMENT

(11/27/63 TO 5/31/64)

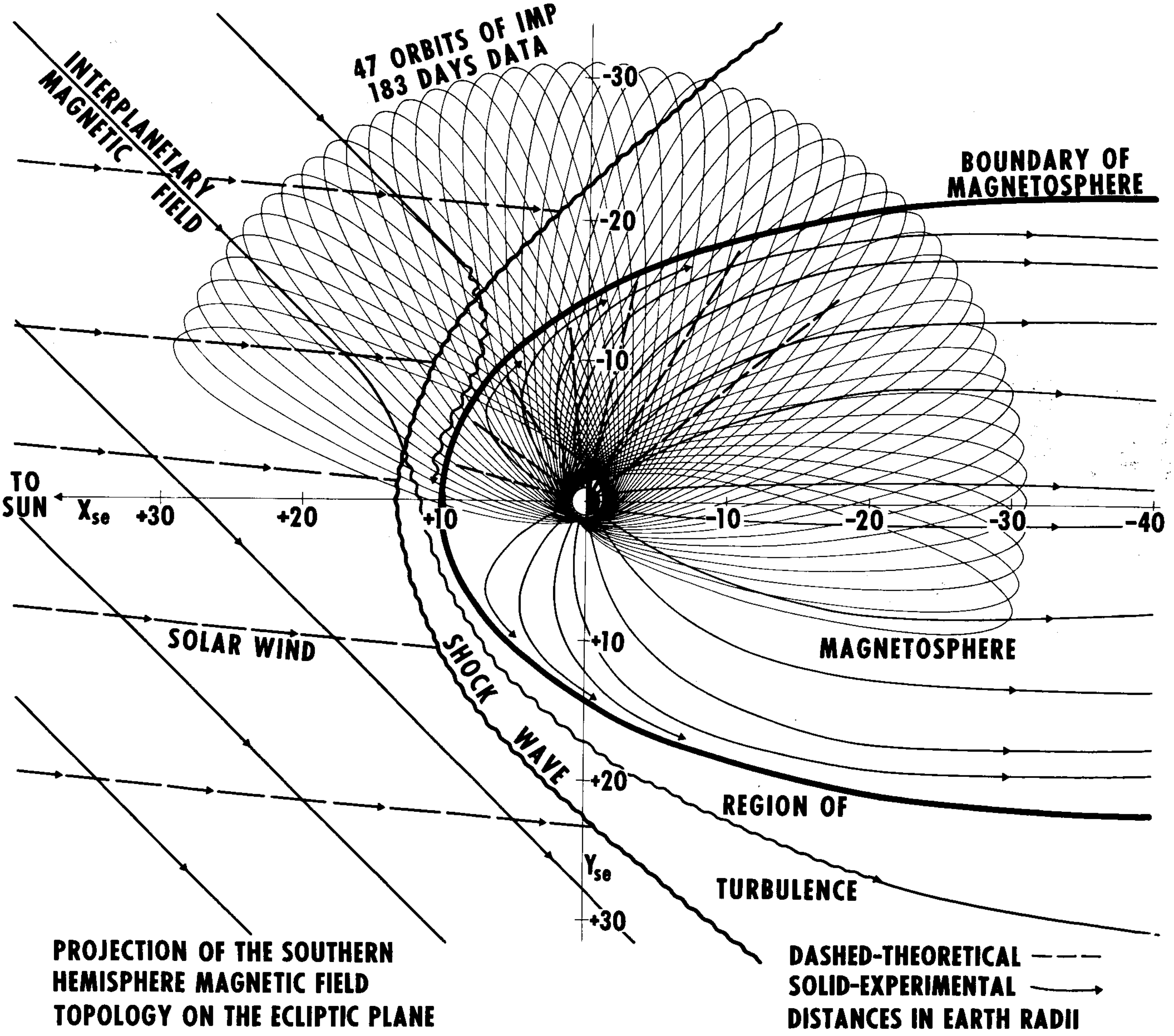


Figure 13

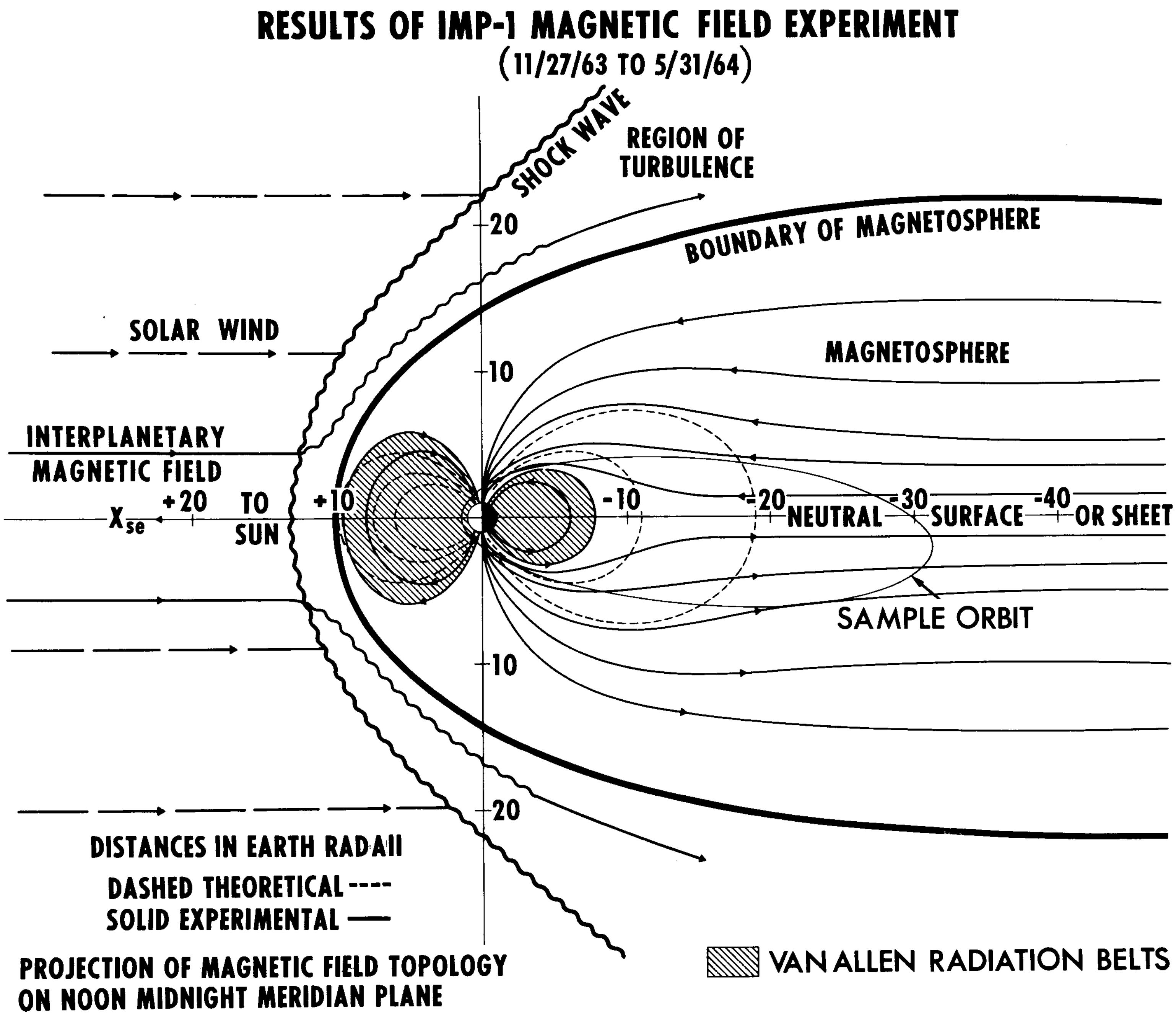

RESULTS OF IMP-1 MAGNETIC FIELD EXPERIMENT
(11/27/63 TO 5/31/64)
SHOCK WAVE
REGION OF TURBULENCE
BOUNDARY OF MAGNETOSPHERE
SOLAR WIND
MAGNETOSPHERE
INTERPLANETARY MAGNETIC FIELD
X se
+20
TO SUN
+10
-10
-20
NEUTRAL
-30
SURFACE
-40
OR SHEET
SAMPLE ORBIT
20
10
10
20
DISTANCES IN EARTH RADAII
DASHED THEORETICAL ----
SOLID EXPERIMENTAL ——
PROJECTION OF MAGNETIC FIELD TOPOLOGY
ON NOON MIDNIGHT MERIDIAN PLANE
VAN ALLEN RADIATION BELTS

Figure 14